Detection of Oil Spills and Underwater Natural Oil Outflow Using Multispectral Satellite Imagery

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Abstract

This application paper demonstrates the capabilities of multispectral remote sensing images on detecting oil spills and underwater natural oil outflows in oil potential areas. An object based method for oil spill detection using high or very high multispectral images has been developed. The method exploits the knowledge provided by the systematic photo-interpretation of the temporal, spectral and spatial features of the high or very high resolution multispectral datasets. The developed method has been proved to work well in very high resolution satellite images such as IKONOS, QuickBird, RapidEye, and WorldView2, as well as high resolution satellite images (Landsat TM). When repeatedly applied on sequential multispectral imagery, the developed method can reveal potential natural underwater oil outflows. A large unknown systematic natural oil outflow near the Zakynthos island (Greece) has been discovered and served as the best proof for the evaluation of the developed oil spill detection method.

Keywords

Multispectral; Hyperspectral; Oil Spills; Oil Outflow; Obia

Introduction

Detection of oil spills is important for both oil exploration and environmental protection. Multispectral and hyperspectral remote sensing imagery (mostly airborne) have repeatedly been used to identify and study oil spill occurrences on seawater. There have been several studies concerning oil spills. Carnesecchi et al (2008) have performed an extensive interpretation of oil spills and their appearance variations. Palmer et al (1994) analyzed an oil spill event with Compact Airborne Spectrographic Imager (CASI) and concluded that the spectrum from 440 to 900 nm is effective to detect the marine oil spill. Zhao et al (2000) concluded that reflectance of various kinds of offshore oil slicks present peaks in the spectral regions from 500 to 580 nm. Salem F. (2003) has demonstrated that the increase of oil quantity causes light absorption to increase, and thus the reflectance in the visible bands is reduced. The near infrared electromagnetic spectrum region from 600 to 900 nm provides the greatest possibility for oil spill detection using remote sensing techniques. YingCheng et al (2008) studied the change of reflectance spectrum of artificial offshore crude oil slick with its thickness and concluded that spectral characteristics of oil spills are very distinct at 550 and 645 nm. Bradford et al (2011) have developed an automatic oil spill detection method using multispectral imagery and Svejkovsky et al (2008 and 2012) presented a real time method to estimate the oil slick thickness of crude oils and fuel oils using multispectral sensor. The proposed algorithm showed that oil thickness distributions up to 200-300 μm can be mapped with accuracy of up to 70%.

In the framework of a relevant Research Project (namely ARGOMARINE, FP7-CP-FP, Grant Agreement number: SCP8-GA-2009-234096) (Cocco M., 2013) the Remote Sensing Laboratory of the NTUA a) has developed a methodology for the detection, identification, mapping and thickness estimation of oil spill events, using very high resolution hyperspectral CASI-550 images, and b) has investigated potentials of high (Landsat TM) and very high (IKONOS, QuickBird, RapidEye and WorldView2) resolution satellite multispectral images for oil spill and natural oil outflows detection. Motivation for the multispectral research was the increased temporal resolution of such images, since nowadays each place is much more frequently viewed by multispectral satellite sensors. The temporal coverage of these satellites, either by a single satellite (for example RapidEye) or combined, can be daily. Thus, multispectral imagery after appropriate processing could serve as a tool for the continuous monitoring of the marine environment.

In this work, only the research with satellite multispectral imagery will be presented. Towards this

direction, various very high resolution multispectral images of Beirut (Lebanon), an area with known oil spill events, have been purchased in order to be used for developing a multispectral oil spill detection method. Furthermore, multispectral images of the island of Zakynthos (Greece) have also been purchased in order to apply and test the method in an area that is known to have frequent natural oil spill occurrences. The temporal, spectral and spatial features of the multispectral datasets have been explored in order to exhibit potentials of photo-interpretation in detecting oil spills and oil natural outflows. Photo-interpretation provided valuable knowledge on oil spill and oil outflow appearances in multispectral images. Thus, a method has been developed that relies on object based image analysis (OBIA) and exploits this knowledge.

The method has been evaluated using very high resolution satellite images such as IKONOS, QuickBird, RapidEye, and WorldView2, as well as high resolution satellite images (Landsat TM). With its application, known oil spills as well as natural oil outflows have been successfully detected. Moreover, using the images of the island of Zakynthos, a large unknown systematic natural oil outflow near the island has been discovered and served as the best proof for the evaluation of the developed oil spill detection method. Through this research, it was proven that systematic photo-interpretation and/or processing of high and very high resolution multispectral images can detect oil spills and reveal natural oil outflows on the seawater surface.

The Oil Spill Detection Method

An automatic oil spill detection method, which relies on object based image analysis, has been developed. Since the method exploits knowledge provided by the photo-interpretation of very high resolution multispectral as well as hyperspectral imagery, before its description, the key photo-interpretation observations are presented.

Photo-interpretation Results

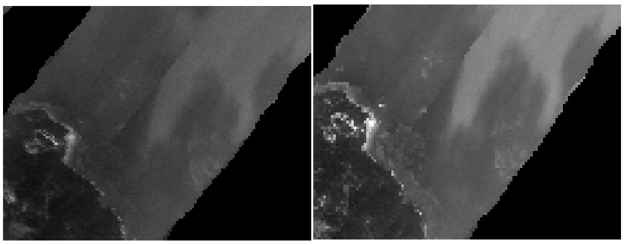
Thorough photo-interpretation of oil spill occurrences has been carried out using IKONOS, QuickBird, RapidEye and WorldView multispectral images which present known oil spill events. Various sea surface roughness levels were depicted in these images. Photo-interpretation has also been supported by the detailed spectral information provided by CASI-550 hyperspectral imagery which has been acquired for the ARGOMARINE project over an area with natural oil spills (FIG. 1). During this hyperspectral image acquisition 96 adjacent spectral bands were acquired in the 400-1000 nm spectral region.

The first observation on the hyperspectral imagery is that oil spills appear brighter than seawater in all the CASI-550 acquired bands. What has also been observed is that within the blue-green region of the spectrum (400 to 600 nm) there is a significant reflectance from the sea bottom. Over the 600 nm the bottom interference is minimized and eventually eliminated after the 660 nm. The spectral region between 660 and 760 nm (upper red to near infrared region) is the best for oil spill identification through photo-interpretation in coastal areas. Within this region the sea bottom interference is eliminated while the oil spill appears significantly brighter than seawater. Above 760 nm (near infrared region) the water reflectance significantly drops and the image suffers from noise. It is more difficult to identify oil spill occurrences within this region. All these observations are evident to the following sequence of CASI-550 images. A sequence of images from 440 to 800 nm is shown on FIG. 1. The natural oil spill occurrences have been marked on sub-figures (g) to (j). Most of the very high resolution multispectral sensors have bands that span across this red-near infrared region (660 to 760 nm) and therefore it should be possible to observe any oil spill occurrences using multispectral images.

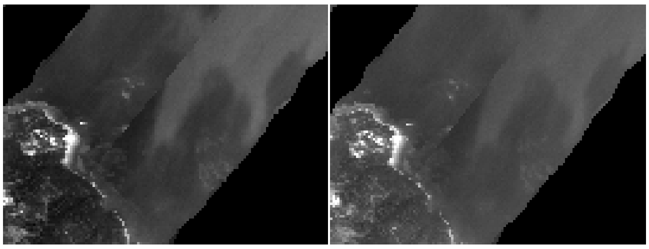
Moreover, the following key observations have been obtained by the systematic photo-interpretation of the multispectral and the hyperspectral imagery:

- Attention should be given to avoid the confusion of oil spills with light clouds. A cloud masking methodology should be applied on the images used in case that clouds are depicted (a thermal band would be very useful for this procedure).
- Discrimination of seawater and oil spill solely based on their brightness difference is not possible.
- The oil spill occurrence areas have significantly higher local standard deviation values due to intensive glint effect and therefore they can be highlighted using a local standard deviation filter (FIG. 2b). This is particularly useful in case that agitated seawater is depicted in the image.
- In case of rough sea, the application of a Gaussian smoothing filter can significantly improve the oil spill identification.

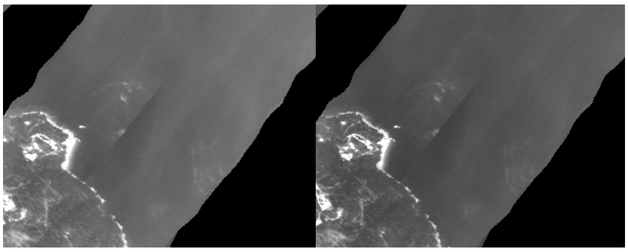
- Oil spills can also be confused with high concentration areas of chlorophyll-a. But, the oil spill occurrence areas present low values in the [blue band]/[green band] ratio and the [blue band]/[red band] ratio (FIG. 2c). Since high values in these ratios can be used to highlight chlorophyll-a concentration in deep and shallow waters relatively (Cannizaro et al, 2006), (Wernand et al, 1998), the discrimination of an oil spill occurrence from chlorophyll-a concentration is feasible.



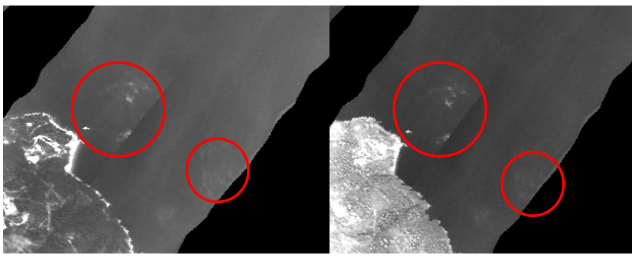
(a) 440 nm(b) 480 nm



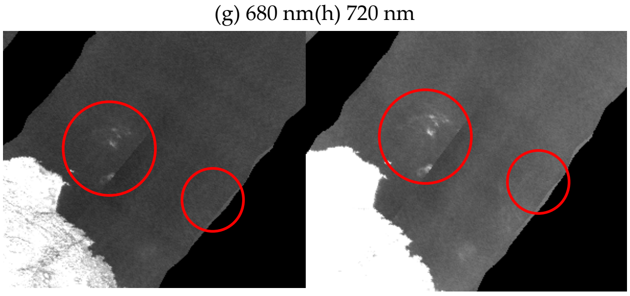
(c) 520 nm(d) 560 nm



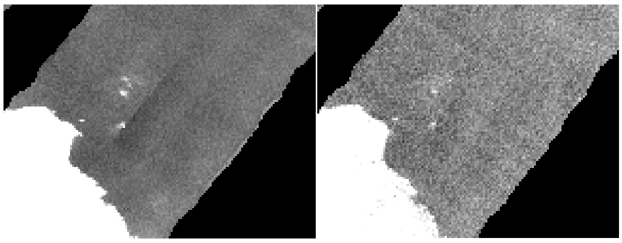
(e) 600 nm(f) 640 nm



(g) 680 nm(h) 720 nm

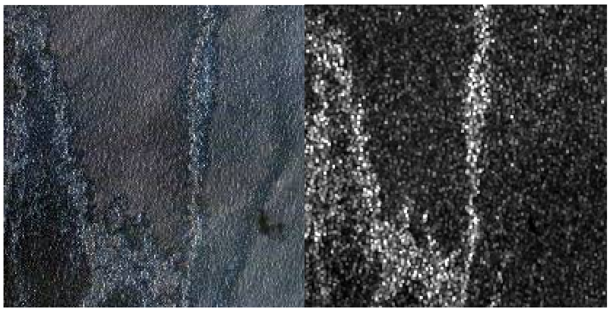


(i) 760 nm(j) 800 nm

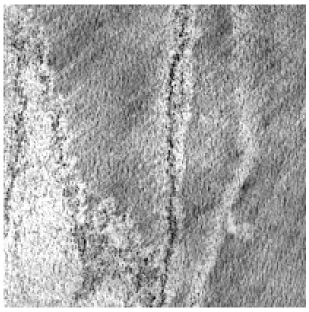


(k) 880 nm(l) 960 nm

FIG. 1 A SEQUENCE OF CASI-550 IMAGE BANDS FOR THE AREA OF KERI IN LAGANAS BAY. THE NATURAL OIL SPILL OCCURRENCES HAVE BEEN MARKED ON IMAGES (g) TO (j).



(a) (b)



(c)

FIG. 2 DETAIL OF THE QUICKBIRD IMAGE OF LEBANON OF JULY 22ND, 2006. (a) ORIGINAL IMAGE, (b) LOCAL STANDARD DEVIATION 9X9 FILTER, (c) [BLUE BAND]/[RED BAND] RATIO

The Developed Method

The aforementioned observations can establish a set of rules for the characterization of an appearance as oil spill. The best method to incorporate all of the above observations in a method for oil spill detection is the use of Object Based Image Analysis (OBIA). The image segmentation, which is the first step in OBIA, creates image objects for which all the values required for the application of the rules that can be calculated and used to classify the image. Moreover, basic advantages of object based classifications are the utilization of different scales of segmentation (multiresolution segmentation) as well as class related features.

The object oriented classification method for oil spill detection on multispectral images has been developed using a relevant software package, eCognition. Two basic classes have been defined: *Land* and *Sea*. The *Sea* class has been classified into three subclasses: *Seawater*,

Possible Chlorophyll-a concentration and *Oil spill*.

The following steps summarize the object based classification method for the oil spill detection on very high resolution multispectral images:

- Initially, the multi-resolution segmentation of the multispectral image takes place. Two segmentation levels are created, one with small size image objects and another with much larger objects (at least 20 times larger than the fine objects). The segmentation mostly takes into consideration the spectral information of the image pixels but also tries to keep the objects relatively smooth shaped. Therefore, a weight of 0.8 is given to the color and a weight of 0.2 is given to the shape of the objects during image segmentation (the weights of these two segmentation criteria sum to one). As far as it concerns the shape parameter, setting the desired smoothness weight to 0.5 and desired compactness weight to 0.5 is usually the best choice. Depending on the sea roughness, the shape compactness weight may have to be increased in order to get normal shaped objects.

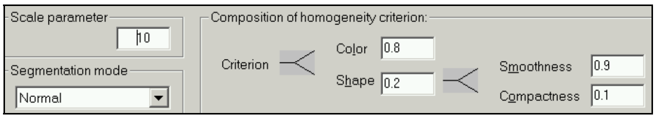


FIG. 3 THE MULTIRESOLUTION SEGMENTATION PARAMETERS

- Two major categories (*Land* and *Sea*) are classified based on the Normalized Difference Water Index 2 (McFeeters S. K., 1996):

  NDWI2=([green band]-[near infrared])/([green band]+[near infrared band])

- Then the *Sea* class is subdivided into three subclasses. The *Oil spill* class is the first to be defined. An image object is classified as an *Oil spill* when:
  - The standard deviation of the image object is higher than a certain value*
  - The ratio of the blue band and the red band is lower than a certain value*
  - The object is bright enough, i.e. the brightness of the image object is high compared to the average scene brightness or the average brightness of its super object (an overlaying object of much larger scale)
  - The image object is not very close to the sea shore (this rule is necessary as image objects close to the sea shore present high standard deviation values)
- The image objects that have not been classified as oil spills are checked according to a fluorescence index i.e. [blue band]/[green band] or [blue band]/[red band] and are classified as *Possible High Chlorophyll-a concentration* if the index is higher than a certain value*
- The rest of the image objects is classified as seawater

The values with asterisk (*) can be standardized for images from a specific multispectral sensor and whose values have been atmospherically corrected and converted to surface reflectance or have been processed by a relative radiometric normalization algorithm (RRN).

The general schematic diagram of the developed OBIA oil spill detection method is shown in FIG. 4.

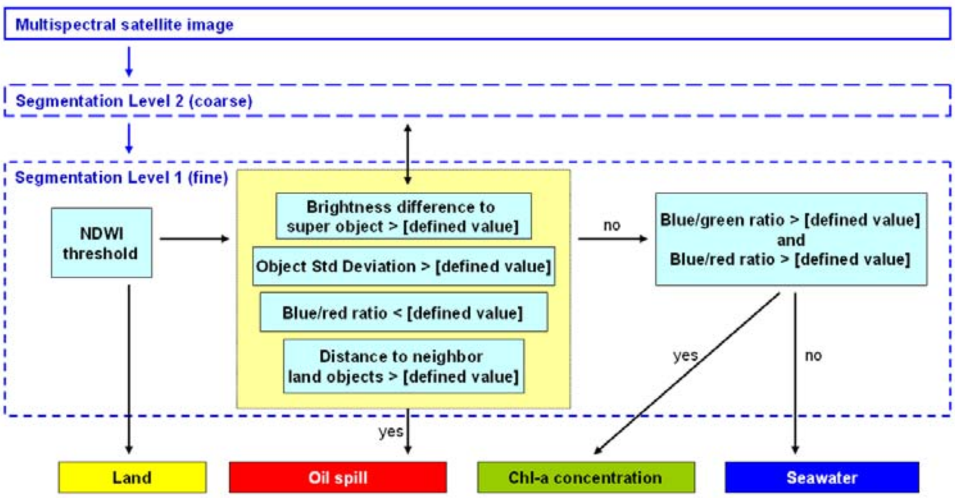


FIG. 4THE DEVELOPED OIL SPILL DETECTION PROCESS

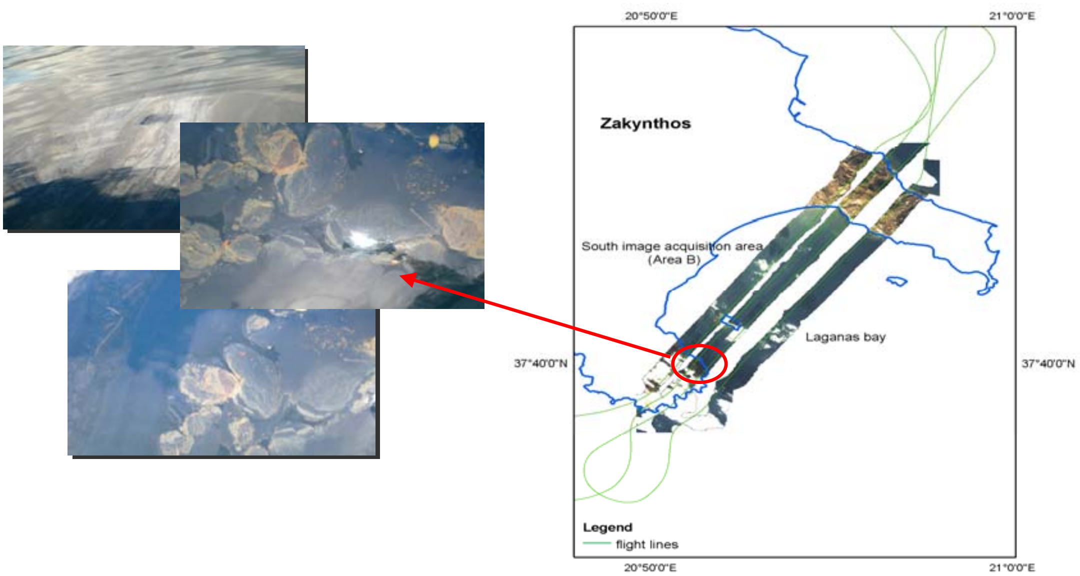


FIG. 5 NATURAL OIL SPILL OCCURRENCES IN LAGANAS BAY (LEFT) AND HYPERSPECTRAL IMAGE ACQUISITIONS OVER THE ZAKYNTHOS ISLAND (RIGHT)

The Dataset

For the needs of this research, various very high resolution multispectral images of Beirut (Lebanon), an area with known oil spill events, have been purchased in order to apply photo-interpretation and develop an oil spill detection method for very high resolution multispectral images. Furthermore, multispectral images of the island of Zakynthos have also been purchased in order to test the method in an area that is known to have frequent natural oil spill occurrences. For example, in FIG. 5, a small natural oil spill is shown near the area of Keri, in Laganas bay, in Zakynthos. The pictures were taken in December 2011, when in situ inspections and spectroradiometer measurements have been carried out from a boat. On the same day, the CASI-550 hyperspectral images which are shown in FIG. 1 and FIG. 5 have also been acquired by the Remote Sensing Laboratory of the NTUA.

Table 1 summarizes the multispectral images which have been used for this work, and then lists the dates of acquisition and also designates whether there is an oil spill occurrence in an image or not, after thorough photo-interpretation of the images.

TABLE 1 VERY HIGH RESOLUTION MULTISPECTRAL IMAGES

Location	Satellite/Sensor	Date of acquisition	Oil spill event
Lebanon	IKONOS	5 August 2006	**yes**
	QuickBird	22 July 2006	**yes**
Zakynthos	RapidEye	13 June 2009	**yes**
		15 July 2009	**yes**
		16 July 2011	**yes**
		1 October 2011	no

In order to test the developed oil spill detection methodology using lower resolution multispectral images, a series of Landsat TM images has been downloaded from the USGS Global Visualization Viewer (http://glovis.usgs.gov/). The following high resolution Landsat TM and ETM+ images of the island of Zakynthos have been used for this work. table 2 lists the dates of acquisition of the Landsat images and also designates whether there is an oil-spill occurrence in an image or not, after thorough photo-interpretation of the images.

The relative radiometric normalization algorithm (RRN) (Karathanassi et al, 2011) has been applied on each dataset in order to standardize the threshold values required by the method for each sensor.

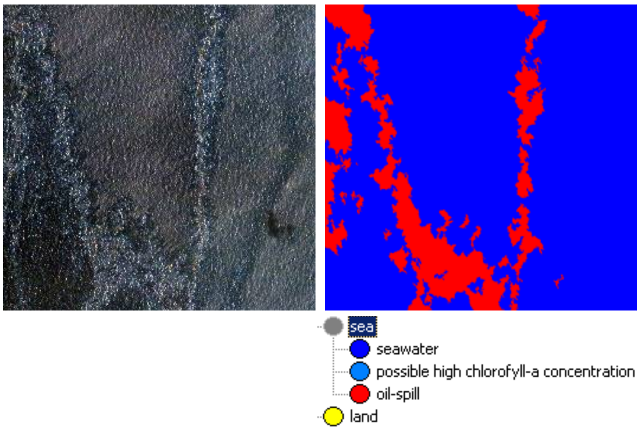
TABLE 2 LANDSAT TM AND ETM+ IMAGES

Satellite/Sensor	Date of acquisition	Oil spill event
Landsat 4-5 TM	8 August 1986	**Yes**
	16 August 2003	no
	23 August 2003	**yes**
	31 July 2009	**yes**
Landsat 7 ETM+	20 June 2012	**yes**
	6 July 2012	**yes**

Implementation and results

Oil Spill Detection

The proposed object based oil spill detection method has been applied successfully on the images of Beirut. FIG. 6 and FIG. 7 show color composites of QuickBird and IKONOS multispectral satellite images that present different appearances of sea state and oil spills, as well as the oil spill detection method results.



(a) (b)

FIG. 6 OIL SPILL DETECTION ON THE LEBANON QUICKBIRD IMAGE OF JULY 22ND, 2006. a) COLOR COMPOSITE (RED: 660.0NM, GREEN: 560.0NM, BLUE: 485.0NM), b) OIL SPILL DETECTION MAP

(a) (b)

FIG. 7 OIL SPILL DETECTION ON THE LEBANON IKONOS IMAGE OF AUGUST 5TH, 2006. a) COLOR COMPOSITE (RED: 667.0NM, GREEN: 551.0NM, BLUE: 475.0NM). b) OIL SPILL DETECTION MAP

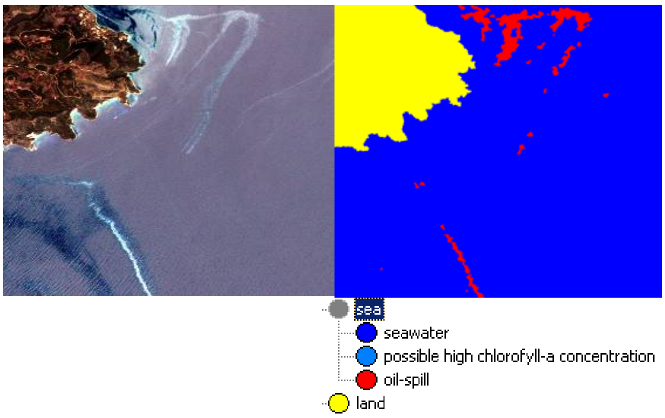


FIG. 8 OIL SPILL DETECTION ON THE RAPIDEYE IMAGE ACQUIRED ON JUNE 13TH 2009. (LEFT IMAGE: SATELLITE IMAGE, RIGHT IMAGE: OIL SPILL DETECTION MAP)

The method has also been applied successfully on the very high resolution RapidEye images of Zakynthos. FIG. 8 shows the results of the application of the described method on the RapidEye images of Zakynthos, acquired on June 13th 2009. The observed natural oil spills inside Laganas bay have been successfully detected in accordance to photo-interpratation results. Moreover, one bigger oil spill has been detected 6 km south of the Laganas Bay, in all images.

The method has also been applied successfully on very high resolution RapidEye images of Zakynthos, on which no oil spills have been observed by photo-interpretation. The application of the class hierarchy, which has been used by the proposed method, with no changes to the values of the object based classification rules, provided correct results (FIG. 9).

FIG. 9 OIL SPILL DETECTION ON THE RAPIDEYE IMAGE ACQUIRED ON OCTOBER 1ST 2011. (LEFT IMAGE: SATELLITE IMAGE, RIGHT IMAGE: OIL SPILL DETECTION MAP)

In order to test the developed oil spill detection methodology using lower resolution multispectral images as well as to further investigate the big oil spill occurrence south of the Laganas bay in Zakynthos island, the Landsat TM images which are listed in table 2 have been used.

FIG. 10 OIL SPILL DETECTION ON THE LANDSAT TM IMAGE ACQUIRED ON AUGUST 8TH 1986. LEFT IMAGE: SATELLITE IMAGE 3,2,1(RGB), RIGHT IMAGE: OIL SPILL DETECTION MAP

TABLE 3 INDICATIVE VALUES USED FOR THE OBJECT BASED CLASSIFICATION RULES (ALL IMAGES HAVE BEEN SCALED TO 8BIT RADIOMETRIC RESOLUTION)

	Very high resolution images (RapidEye, QuickBird, IKONOS)	High resolution images (Landsat TM)
Standard Deviation (Red band)	>4.5 fuzzy range: (4, 5)	>0.75 fuzzy range: (0.5, 1)
NDWI	>0 fuzzy range: (-0.1, 0.1)	>0 fuzzy range: (-0.1, 0.1)
Blue band/Red band ratio	<2 fuzzy range: (1.8, 2.4)	<4.35 fuzzy range: (4.2, 4.5)
Mean difference to super objects (Red band)	>0 fuzzy range: (-0.2, 0.2)	>1.75 fuzzy range: (1, 2.5)
Distance to *land* objects	The distance to *land* objects depends on the image scale and on the segmentation scale. In most case a value greater than 5 has been used	

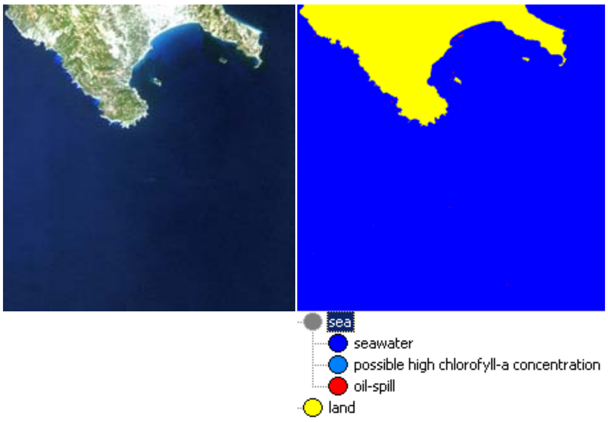


FIG. 11 OIL SPILL DETECTION ON THE LANDSAT TM IMAGE ACQUIRED ON AUGUST 16TH 2003. LEFT IMAGE: SATELLITE IMAGE 3,2,1(RGB), RIGHT IMAGE: OIL SPILL DETECTION MAP

With some changes on the segmentation and the threshold values of the object based classification rules (table 3), the same method has been proved to be applicable on high multispectral satellite images, i.e. Landsat TM. This is very encouraging as with the Landsat Data Continuity Mission this kind of satellite data will be available at a regular basis.

The method provided results consistent to table 2. In FIG. 10, the Landsat image of August 8th 1986 is shown. Small natural outflows inside the Laganas bay have not been detected, either because they did not exist on this particular day or due to the lower spatial resolution of the sensor. However, the bigger oil spill outside the bay has been detected. The same class hierarchy which has been used for the classification of the Landsat image of August 8th 1986, with no changes to the values of the object based classification rules, when applied on a Landsat TM image on which no oil spills have been observed by photointerpretation (e.g. the Landsat TM image acquired on August 16th 2003), provided correct results (FIG. 11) with only few false alarms near the shore.

Discovery of Unknown Systematic Oil Outflows

By observing the results of the proposed oil spill detection method on the RapidEye datasets (FIG. 8, FIG. 12), an oil spill has been systematically detected 6 km south of the area of Keri in Laganas bay.

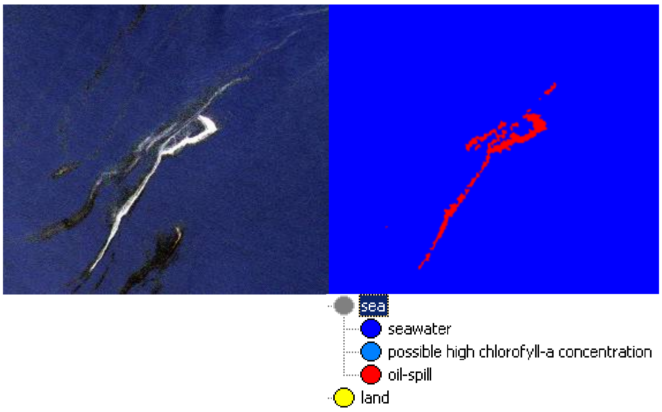


FIG. 12 OBJECT BASED OIL SPILL DETECTION ON THE RAPIDEYE IMAGE ACQUIRED ON JULY 15TH 2009. (LEFT IMAGE: SATELLITE IMAGE, RIGHT IMAGE: OIL SPILL DETECTION MAP)

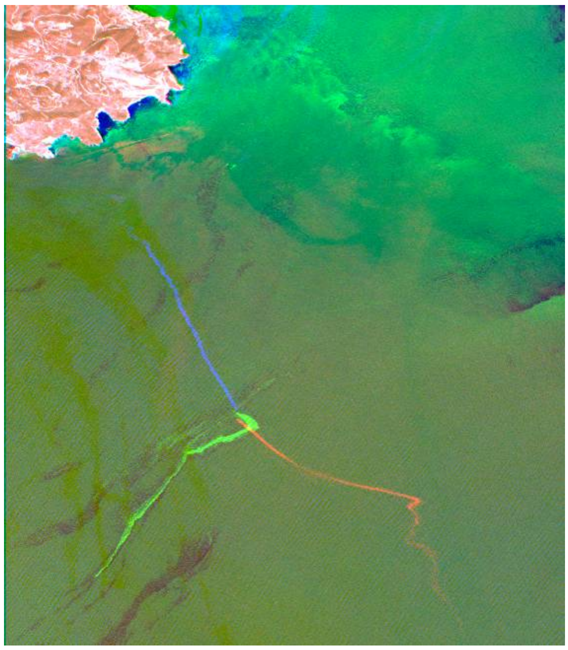


FIG. 13 MULTITEMPORAL COLOR COMPOSITE OF THE THREE RAPIDEYE IMAGES OF ZAKYNTHOS: JULY 13TH 2009 (BLUE), JULY 15TH 2009 (GREEN) AND JULY 16TH 2011 (RED). THE OIL SPILL OCCURRENCES NEAR ZAKYNTHOS START FROM A SPECIFIC POINT AT THE OPEN SEA, 6 KM SOUTH OF KERI.

Moreover, in all images, the detected oil spills seemed to start from a specific point (Latitude: 37° 36', Longitude: 20° 52') at the open sea with an estimated depth of 560 meters according to the SRTM30_Plus bathymetry data. This becomes also obvious on the multitemporal color composite of the red-edge band of the three RapidEye images (FIG. 13).

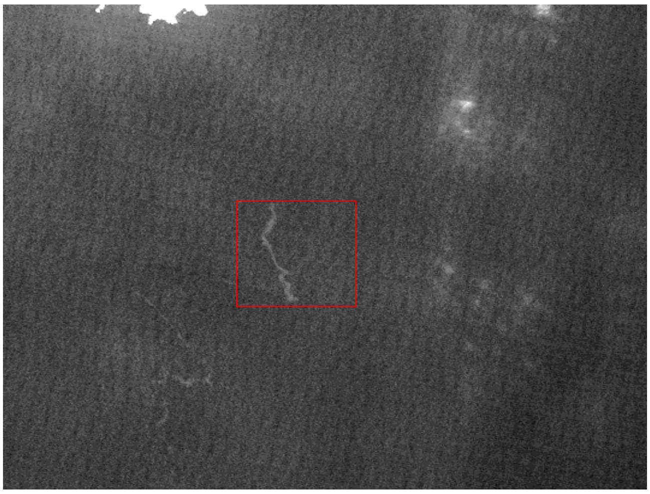


FIG. 14 THE DISCOVERED NATURAL OIL OUTFLOW ON THE LANDSAT TM IMAGE ACQUIRED ON JULY 31ST 2009 (RED BAND).

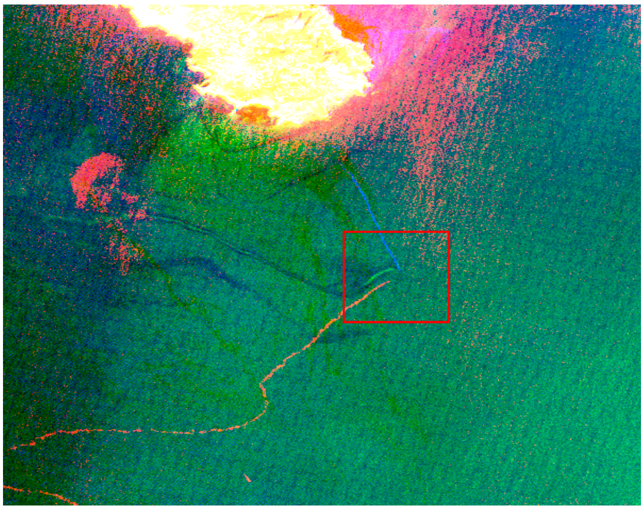


FIG. 15 MULTITEMPORAL COLOR COMPOSITE OF LANDSAT TM IMAGE ACQUIRED ON AUGUST 8TH 1986 (RED), LANDSAT TM IMAGE ACQUIRED ON AUGUST 23RD 2003 (GREEN) AND RAPIDEYE IMAGE ACQUIRED ON JULY 13TH 2009 (BLUE).

The same oil spill occurrence systematically has been detected on the Landsat images using either photo-interpretation or the proposed method. FIG. 14 shows the discovered natural outflow as depicted from the Landsat TM sensor on July 31st 2009. The multitemporal color composite of FIG. 15 reveals the systematic occurrence of the natural outflow from 1986 to 2009. Two Landsat images (red band), acquired on August 8th 1986 and August 23rd 2003 relatively, and one RapidEye image (red-edge band), acquired on July 13th 2009, have been used to create this composite image. Using two Landsat 7 ETM+ images (red band), acquired on July 6th 2012 and June 20th 2012, it has been certified that the natural outflow was still active in 2012. The ETM+ sensor of Landsat 7 satellite has a known malfunction that causes stripes on the images, nevertheless the natural outflow could easily be observed.

The specific geographic point that the big oil spill occurrence starts from in all the images, as well as the wide temporal window of the datasets in which it has been observed, leads to the conclusion that a natural outflow exists in the area which was not known until now. Both the above mentioned criteria are significant to characterize an oil spill as natural oil outflow. The spatial resolution of the images, in which the outflow has been detected, can be considered as a measure of the quantity of the oil outflow. In Zakynthos case, the natural oil outflow is quite large since the oil spill occurrences appear in Landsat images (30m resolution) as tails of many kilometers (usually 10 to 20 km).

More Landsat TM images (not listed in table 2) of various dates have been downloaded from USGS and photo-interpreted, in order to further investigate the discovered natural oil outflow. One very interesting observation about the discovered natural outflow is that it appears only during the summer period. This natural outflow occurrence was not apparent in any of the Landsat TM images that were acquired between October and April. It does appear sometimes in May and September, but it usually is evident during the three summer months. This can be explained from the chemistry point of view as follows. The oil viscosity depends on the temperature. Low temperature will cause high viscosity and as a result the outflow may be blocked or mercurial. On the other hand, higher temperatures will cause lower oil viscosity which will lead to a continuous oil outflow. The unusual very long narrow shaped occurrences of this natural oil outflow must be caused by a generally high oil viscosity.

The natural oil outflow was also verified by spot test from a boat on August 1st, 2012. Water samples have also been taken for chemical analysis which verified the presence of hydrocarbons.

Conclusions

Nowadays, the time resolution of very high resolution satellite multispectral images, such as RapidEye,

IKONOS, Quickbird and WorldView2 images has significantly increased. Therefore, this kind of imagery, along with appropriate processing and analysis techniques, can serve as a tool for the continuous monitoring of the marine environment.

In this study, the investigation of very high resolution satellite multispectral images and high resolution satellite images such as Landsat to detect oil spills through photo-interpretation means has been initially carried out. Moreover, an automatic oil spill detection method which exploits knowledge obtained by photo-interpretation has been developed. The oil spill detection method based on Object Based Image Analysis (OBIA) can be fully automated for images from a specific multispectral sensor whose values have been atmospherically corrected and converted to surface reflectance or have been processed by a relative radiometric normalization algorithm (RRN). The oil spill detection method has been developed using very high resolution multispectral imagery and it has also been adapted to high resolution data such as Landsat TM images. Moreover, spatial and temporal criteria have been established on both photo-interpretation and automatic method results in order to characterize an oil spill as natural oil outflow.

Both photo-interpretation and the proposed automatic method have been successfully applied on very high resolution multispectral images of Beirut (Lebanon), an area with known oil spill events, as well as on very high resolution multispectral images of the island of Zakynthos, focusing on the area of Keri which is known to have frequent natural oil spill occurrences. Using the latter images as well as historic Landsat TM imagery, a large unknown systematic natural oil outflow near the Zakynthos island has been discovered and served as the best proof for the evaluation of the developed oil spill detection method. Research showed that the systematic application of the developed oil spill detection method on a sequence of high and very high resolution multispectral images can reveal natural oil outflows on the seawater surface.

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